

Figure 4-8 The concordant igneous rock body in the bottom drawing could be formed either by intrusion or as a lava flow that was later covered by sediment.

### 4.3 Volcanoes and Other Volcanic Landforms

Volcanic eruptions form a wide variety of landforms, including several different kinds of volcanoes and lava plateaus. Additionally, many islands, including all of the Hawaiian Islands, Iceland, and most of the islands of the southwestern Pacific Ocean, were constructed entirely by volcanic eruptions. Occasionally a violent eruption destroys a landform, as in the 1980 eruption of Mount St. Helens, when most of the mountaintop was blown away.

#### Structures and Textures of Lava Flows

Recall that magma is less dense than the rock formed when it solidifies. Thus, as magma solidifies, it shrinks, forming cracks that grow as the rock continues to cool.

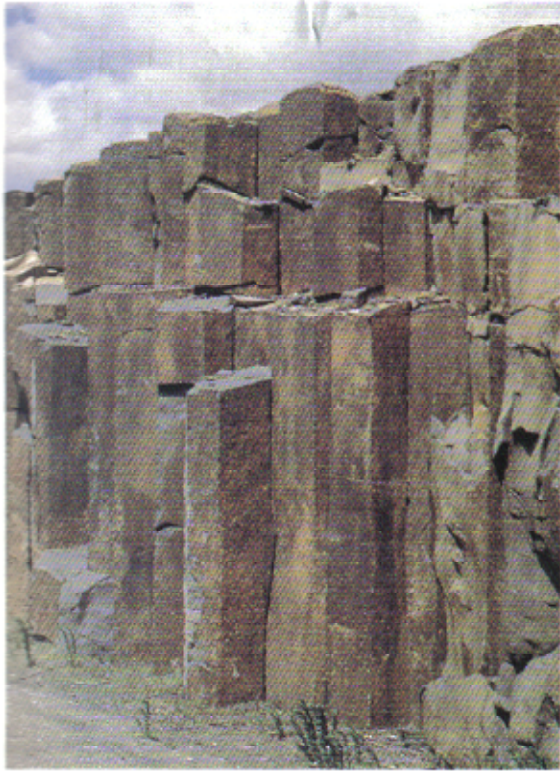
Geologists have watched fresh lava cool and solidify in lava lakes in Hawaii. When a solid crust only 0.5 centimeter thick forms on the surface of the glowing liquid lava, five- or six-sided cracks begin to develop in the crust. As the lava cools and becomes solid, the cracks grow downward to hotter

zones where the last bit of melt is solidifying. The cracks that commonly develop in lava flows and shallow sills, called **columnar joints**, are regularly spaced and intersect to form five- or six-sided polygonal columns (Fig. 4-9).

Lava can develop different textures depending on its viscosity and rate of cooling. Lava with low viscosity may continue to flow as it cools and stiffens, forming basalt with smooth, often glassy surfaced, concentric wrinkled or "ropy" ridges. This is called **pahoehoe** lava (Fig. 4-10). If the viscosity of the lava is slightly higher, it may cool and partially solidify but continue to flow as a slow-moving mixture of solid rock and liquid lava. As a result, **aa** lava (Fig. 4-11) has a jagged, rubbly, broken surface. Aa lava commonly contains numerous vesicles, so that the rock resembles Swiss cheese. Both pahoehoe and aa are Hawaiian names for the lava types.

When basaltic magma erupts under water, the rapid cooling causes it to contract, forming spheroidal **pillow lava** (Fig. 4-12). Pillow lavas are abundant in the upper layers of oceanic crust where they form as basaltic magma oozes from fissures in the mid-oceanic ridge.





A



B

**Figure 4-9** (A) Columnar basalt in the Columbia River valley exposed in a road cut near Spokane, Washington. (Courtesy of Larry Davis.) (B) Top view of columnar jointed basalt showing polygonal cracking. (Courtesy of Don Hyndman.)

**Figure 4-10** A car buried in pahoehoe lava in Hawaii. (Courtesy of Kenneth Neuhauser.)







## FOCUS ON ➡ Volcanic Activity in the Solar System

Volcanism is not limited to the Earth; many of the planets and moons in our solar system also show evidence of volcanic activity. The smooth, flat "maria" of the moon are not seas as their name implies, but lava plateaus.

The two decades from 1960 to 1980 were a period of intense exploration of the solar system by spacecraft. One of the more exciting photographs obtained during this exploration was a picture of a volcanic eruption in progress on Io, one of the moons of Jupiter (Fig. 1). Io is a small satellite, only two-thirds the size of the Earth's moon and just slightly more dense. Since it is too small to have retained the heat released by radioactive decay in its interior, many observers expected to see a cold, lifeless, cratered, lunar-like surface. The observation of an *active* volcano dispelled this con-

cept. Geologists now believe that Jupiter's intense gravitational field creates tidal motion within Io's interior and that friction from these tidal movements heats the rock sufficiently to form magma.

In 1988, another example of extraterrestrial volcanism was found, this time on the frigid moons of Uranus. Astronomers had mapped several rift valleys on the two moons, Ariel and Miranda. On Earth, volcanic activity is common in rift valleys, but the small size of the Uranian moons seemed to preclude any possibility of volcanism. However, careful examination of photographs showed that glacial ice seemed to have been extruded from the rifts. Astronomers now believe that a mixture of ice, methane, and ammonia erupts from the rifts much as molten magma erupts on the surface of the Earth.

Figure 1 Volcanic eruption on the surface of Io, a moon of Jupiter. The eruption is on the upper left edge of Io. (Courtesy of NASA.)

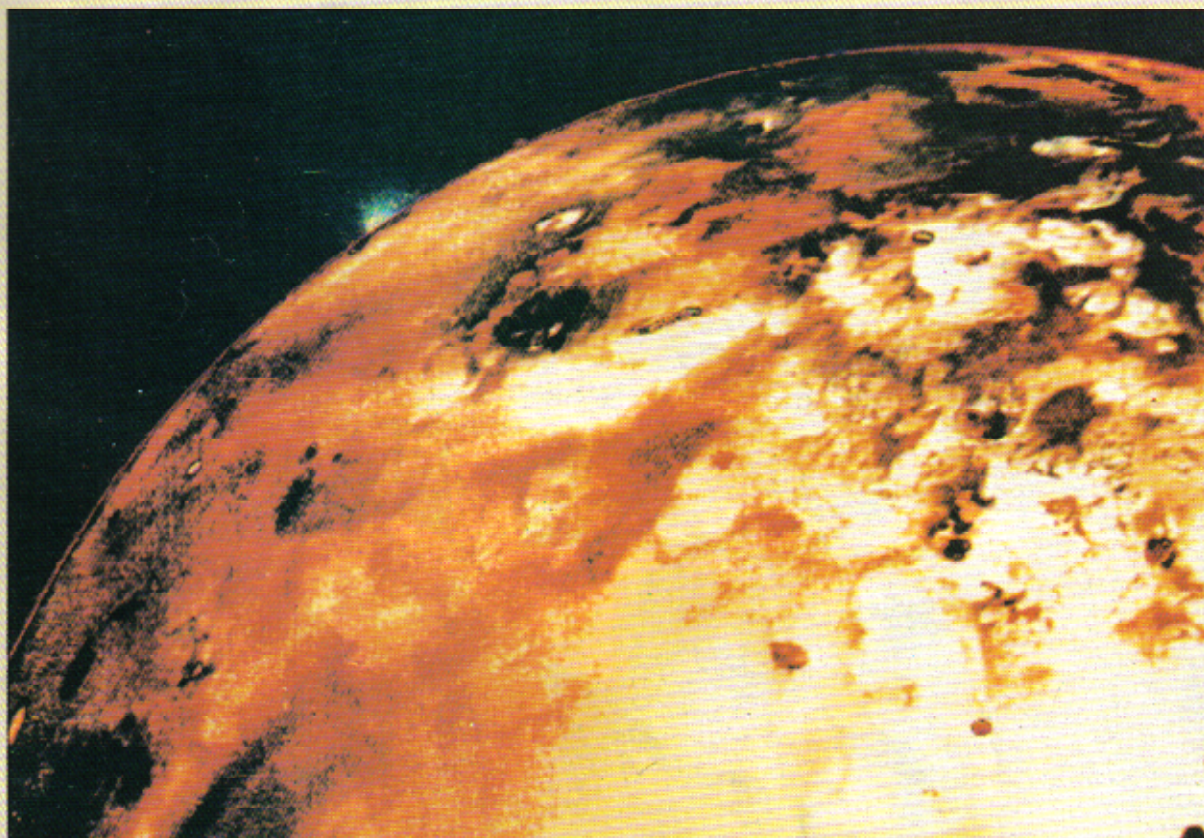






Figure 4-11 Hot aa lava flow in Hawaii. (Courtesy of U.S. Geological Survey, J.D. Griggs.)



Figure 4-12 Pillow lava. (Courtesy of Don Hyndman.)

In addition to flowing lava, a variety of different sized particles may be ejected during a volcanic eruption. Any rock formed when lava or solid rocks erupt explosively is called a **pyroclastic rock**. The particles forming pyroclastic rocks come in a variety of sizes. The smallest are glassy pieces of **fine ash** less than 0.06 millimeter in diameter. **Coarse ash** ranges from 0.06 to 2 millimeters in diameter. Mid-sized particles called **cinders** range from about 2 to 64 millimeters. Still larger fragments called **volcanic bombs** form when small masses of molten lava are hurled out of a volcanic vent. They spin through the air as they solidify and therefore take the form of spindles or spheroids (Fig. 4-13).

Although the words *ash* and *cinder* are used to describe these volcanic particles, they are not the same as the ashes and cinders produced by conventional fires. To appreciate the nature of volcanic ash, consider the following account. In December 1989, Mount Redoubt volcano, southwest of Anchorage, Alaska, erupted. A pilot of a Boeing 747, with 231 passengers aboard, ignored warnings about the rising ash cloud and flew into it. The abrasive particles were sucked into the jet engines. They quickly ground the sharp blades of the compressor into small stubs. Then, exposed to the intense heat in the combustion chamber, the particles melted. Moments later, the liquid solidified as a glass on the cooler turbine blades. As a result, all four engines stalled and the jet fell 4000 meters in 8 minutes. Finally, the pilot was able to restart the engines and fly the disabled craft back to Anchorage where he landed safely.

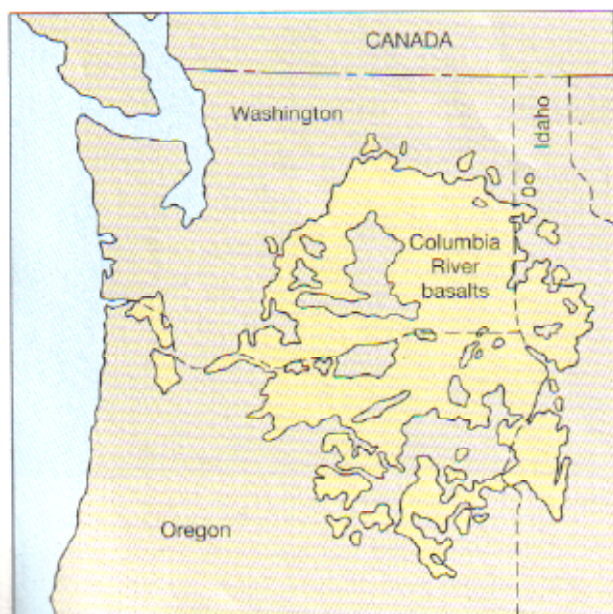
### Flood Basalts

The gentlest, least catastrophic type of volcanic eruption occurs when magmas are so fluid that they simply ooze from cracks at the Earth's surface and flow over the land like water, forming a broad plain or plateau. Basaltic magmas commonly pour out as **flood basalts** which are so named because they cover the landscape like a flood of water. The plateaus created by such lava flows are called **lava plateaus**. An extensive lava plateau forms the Columbia River

Figure 4-13 A volcanic bomb embedded in cinders. The streaky surface of the bomb formed as a blob of magma whirled through the air. (Courtesy of Jack Herbert.)







**Figure 4-14** (A) The location of the Columbia River basalt plateau. (B) Columbia River basalt in eastern Washington. (Courtesy of Larry Davis.)

plateau in eastern Washington, northern Oregon, and western Idaho (Fig. 4-14). This sequence of basalt flows contains 350,000 cubic kilometers of rock, is 3000 meters thick in places, and covers 200,000 square kilometers. It formed over a period of 3 million years, from 17 to 14 million years ago, as layer upon layer of basalt magma oozed from fissures in eastern Washington and Oregon. Each flow formed a layer between 15 and 100 meters thick. Similar large basalt plateaus are found in western India, northern Australia, Iceland, Brazil, Argentina, and Antarctica.

## Volcanoes

If lava is more viscous than that which forms lava plateaus, it will build up into a pile, called a **volcano**, that solidifies before the lava has time to flow outward to form a flat plateau. Volcanoes differ widely in shape, structure, and size (Table 4-1). The opening through which lava and rock fragments erupt is called a **vent**. In many volcanoes the vent is located in a **crater**, a bowl-like depression at the summit of the volcano.

### Shield Volcanoes

If basaltic magma is more viscous than that which forms a lava plateau, but still quite fluid, it will heap up slightly to form a gently sloping volcanic mountain called a **shield volcano**. Shield volcanoes

generally have slope angles between  $6^\circ$  and  $12^\circ$  from horizontal. As a reference, a ski slope for beginning to intermediate skiers is about  $10^\circ$ , and an expert slope may be as steep as  $30^\circ$ . Unless gullies have been formed by erosion, you will find no expert ski runs on a shield volcano; they are simply not steep enough.

During an eruption of a shield volcano, the low-viscosity lava usually flows gently over the lip of the crater or from **fissures**, linear cracks in the sides of the volcano. Volcanic eruptions that occur from vents at or near the top of a volcano are called **central eruptions**. Those that occur from fissures on the flanks of a volcano are called **fissure eruptions**. Despite the fact that eruptions occur regularly in Hawaii, they are normally relatively gentle. Homes and villages are occasionally overrun by lava flows, but the flows advance slowly enough that there is time for people to evacuate. These eruptions are rarely life threatening.

### Cinder Cones

A **cinder cone** is a small volcano, as high as 400 meters, made up of pyroclastic fragments blasted out of a central vent at high velocity.

Cinder cones develop from magma of basaltic to intermediate composition (andesite). They form when large amounts of gas accumulate within rising magmas. When the gas pressure builds up sufficiently, the entire mass erupts explosively, hurling



Table 4-1. Characteristics of Different Types of Volcanoes

Type of Volcano	Form of Volcano	Size	Type of Magma	Style of Activity	Examples
Basalt plateau	Flat to gentle slope	100,000 to 1,000,000 km <sup>2</sup> in area; more than 1800 m thick	Basalt	Gentle eruption from long fissures	Columbia River Plateau
Shield volcano	Slightly sloped 6° to 12°	Up to 9000 m high	Basalt	Gentle, some fire fountains	Hawaii
Cinder cone	Moderate slope	100 to 400 m high	Basalt or andesite	Ejections of pyroclastic material	Parícutín, Mexico
Composite volcano	Alternate layers of flows and pyroclastics	100 to 3500 m high	Variety of types of magmas and ash	Often violent	Vesuvius, Mount St. Helens, Aconcagua
Caldera	Cataclysmic explosion leaving a circular depression called a caldera	Less than 40 km in diameter	Andesite to rhyolite	Very violent	Yellowstone, San Juan Mountains

Active pahoehoe flow in Kalapana Gardens subdivision, December 1986. (Courtesy of U.S. Geological Survey, J.D. Griggs.)





cinders, ash, and molten magma into the air. The particles then fall back around the vent to accumulate as a small mountain of volcanic debris.

As the name implies, cinder cones are symmetrical in shape. They also can be quite steep (about  $30^\circ$ ), especially near the vent where ejected particles pile up (Fig. 4-15). Cinder cones are usually active for only a short period of time because once the gases escape, the driving force behind the eruption is removed. Since these volcanoes are made up of unconsolidated material, they erode easily and quickly. Therefore, they are transient features of the landscape, in a geological time frame.

About 350 kilometers west of Mexico City there is a broad plain with numerous extinct cinder cones. Prior to 1943, there was also a small hole in the ground in one of the level portions of the plain. This hole had existed for as long as anyone could remember, and people grew corn just a few meters away. In February of 1943, as two farmers were preparing their field for planting, smoke and sulfurous gases arose from the hole. As night fell, hot, glowing rocks were ejected, creating a spectacular series of arcing flares like a giant fireworks display. By morning, a 40-meter-high cinder cone had grown in the middle of the cornfield. During the course of the next five days, pyroclastic material was ejected 1000 meters into the atmosphere and the cone grew to 100 meters

in height. Within a few months, a fissure opened at the base of the cone and lava was extruded, burying the town of San Juan Parangaricutiro. Two years later, the cone had grown to a height of 400 meters. After nine years, the eruptions ended, and today the volcano, called El Parícutín, is dormant.

### Composite Cones

Some of the most beautiful and spectacular volcanoes in the world are **composite cones**, sometimes called **stratovolcanoes**. They form by an alternating series of lava flows and pyroclastic eruptions. As explained previously, pyroclastic eruptions tend to form steep but unconsolidated slopes. When these are covered by gentler lava flows, the hard lava rock protects them from erosion and stabilizes them. In addition, the lava flows flatten the angle of the slope, as shown in Figure 4-16.

Composite cones are built up over a cycle of many eruptions over long spans of time. Most of the magma is andesite, which as you recall has an intermediate silica content. However, material with high or low silica content occasionally may erupt from the same vent.

The word *andesite* comes from the Andes, the long mountain chain in western South America. The highest mountain in the Western Hemisphere is Aconcagua (6960 meters) in the southern Andes on

Figure 4-15 Eruption of El Parícutín in February, 1943. (Courtesy of USGS.)

